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53

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ABSTRACT

(U) The article is divided into five main sections, which are as follows: Generation of low-temperature plasma and the control of its parameters; plasma treatment of materials, powder metallurgy; Plasma processes in metallurgy; Plasma remelt of steels and alloys. In the treatment of materials and in metallurgy three kinds of action of the plasma jet are used on the substance: thermal, force (caused by high-speed jet pressure) and chemical. The cost of the energy of a plasma jet is commensurable with the cost of energy of heat sources applied at present in the technology of treatment, for example, an oxyacetylene flame. Thus, the approximate cost of the work of the heat source with 50 kW of power for one hour for an oxyacetylene flame is 3.8 rubles (temperature, 3100 degrees) and for a nitric plasma jet, 2.2 rubles (temperature, 13,000 degrees). To develop and improve plasma processes of the treatment of materials it is necessary to: (a) develop means of active control of processes of the interaction of plasma with the treated material and (b) investigate the physicochemical processes (phase conversions, kinetics of chemical reactions, processes of diffusion, accomodation, sorption etc.) occuring on the surface of the treated material and in the boundary layer of the plasma. Orig. art. has: 11 figures and 2 formulas

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ABSTRACT

(U) An investigation is conducted of the cyclical strength of the base metal and welded samples of the beta -alloy of titanium of the VT15 brand, which are subjected to mechanothermal treatment. An analysis of the obtained data showed that the application of mechanothermal treatment for welded joints of alloy VT15 can considerably increase their longevity. The possibility of the application of metastable titanium beta-alloys in welded constructions is limited in connection with the reduced plasticity of welded joints which is caused by the instability of the beta-phase of the alloy with cooling in the process of welding due to the development of the chemical and physical heterogeneity in the metal of the seam and zone of thermal effect.

DATA HANDLING PAGE

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39-TOPIC TAGS	metal deformation, metal cracking, metal creep, metallographic analysis, niobium base alloy, welding condition
09-TITLE	THE MECHANISM OF THE FORMATION OF HOT CRACKS WITH WELDING OF NIOBIUM ALLOYS
47-SUBJECT AREA	11, 13
42-AUTHOR/CO-AUTHORS	CHERNYSHOV, T. A.; 16-SHORSHOROV, M. Kh.
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ABSTRACT

(U) In a special technological test, used for an estimate of the resistivity of niobium alloys to the formation of hot cracks, measurements of deformations in the process of welding are conducted. The measurements showed that cracks transverse to longitudinal stresses of shrinkage of a welded seam will be formed below the temperature of hardening of the welding bath. In these conditions destruction of the welded seams is close in scheme to destruction with high-temperature creep. A discussion is given of well-known models of intercrystallite destruction with creep in reference to conditions of cooling of the metal of the welded seam, and a hypothesis on the action of the vacancy mechanism of the formation of hot cracks is expressed. The resistivity of different alloys to intercrystallite destruction is determined by the relationship of speeds of slipping and migration of borders of the grains. An important role is played by the composition of alloys, the quantity of impurities of introduction and the character of their distribution in the cast structure. The hypothesis is confirmed by results of metallographic analysis of structures and tests of alloys on a technological sample.

TABLE OF CONTENTS

U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

PLASMA PROCESSES IN METALLURGY AND THE TREATMENT OF MATERIALS

N. N. Rykalin

(Moscow)

A low-temperature plasma jet for the treatment of materials in metallurgy is characterized by high energy and gas-dynamic parameters and their considerable irregularity in length and radius of the jet. The power of a plasma jet is changed within limits of 10^3 to 10^6 W; the enthalpy reaches several 10^6 J/kg; the temperature – 10^4 deg, heat flows – 10^2-10^6 W/cm^2 and velocity – thousands of meters per second. The pressure of the plasma varies from hundredths of an atmosphere to tens of atmospheres, and the dynamic pressure – from hundredths of an atmosphere to several atmospheres. These parameters are easily controlled by electrical and gas-dynamic methods.

In chemical composition the plasma jet can consist of inert (argon, helium, etc.) and chemically active (hydrogen, oxygen, chlorine, methane, nitrogen, steam and others) gases. The composition of the jet and concentration of its component can also be changed in a wide range.

With the observance of special measures the plasma can be very pure. Thus, the contamination of arc hydrogen plasma, applied in processes of restoration, by the material of the electrodes (tungsten and copper) is about 0.005%.

In the treatment of materials and in metallurgy three kinds of action of the plasma jet are used on the substance: thermal, force, which is caused by high-speed jet pressure, and chemical. In a specific technology the determining form can be one of the forms of the a tion and, in certain cases, two or all forms of the jet action.

The cost of the energy of a plasma jet is commensurable with the cost of energy of heat sources applied at present in the technology of treatment, for example, an oxyacetylene flame. Thus, the approximate cost of the work of the source of heat with a power of 50 kW for one hour for an oxyacetylene flame is 3.8 rubles (temperature, 3100°), for a nitric plasma jet – 2.2 rubles (temperature, 6700°), for a plasma jet – 3.8 rubles (temperature, 13,000°).

1. Generation of Low-Temperature Plasma and the Control of its Parameters

At present there is widespread use in technology and research laboratories of plasma generators, in which electrical energy by means of an arc discharge is transformed into energy of the plasma jet. It is necessary, however, to distinguish the two fundamentally different methods of the use in gas discharge for plasma generation.

Formation of a plasma jet in a column of an arc discharge. For this in the energy balance of the gas discharge

$$\sigma E^2 = S(T) + \rho C_p V \operatorname{grad} T - \operatorname{div} \lambda \operatorname{grad} T \tag{1}$$

the convection member, the power of which basically determines the energy content of the plasma jet artificially increases. A schematic diagram (similar plasmatrons are used in welding, cutting, putting on of coverings, spheroidizing, restoration, etc.) of such a plasmatron is shown in Fig. 1. Its elements are electrodes between which there is excited a realtively long arc discharge and a chamber in which the working substance (gas and liquid) is heated by the energy released in the column of the arc [1].

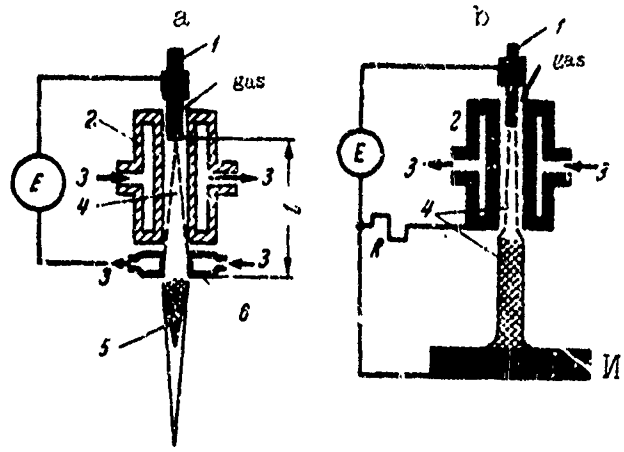

Fig. 1. Diagrams of an arc plasmatrons:
a) with an arc independent of the article,
b) with an arc dependent on the article.
1 – electrode, 2 – channel, 3 – cooling water, 4 – column of the arc, 5 – plasma jet, E – power supply, И – article, R – resistance.

The energy released in the electrode regions of such plasmatrons should be as little as possible, since its increase leads to a lowering of efficiency of the plasmatron and destruction of the electrodes. The internal efficiency, which is determined as the ratio of the power of the plasma jet to the total power of the arc, is 50-80%. Losses are caused by the heat transfer of energy of the arc into electrodes and walls of the discharge chamber. Electrodes of the arc plasmatron are made of copper, tungsten or graphite. The consumption of copper electrodes is 10^{-6}-10^{-9} kg/kJ. Plasma generators stably operate at the flow rate of gas of 10^{-2} to 10^{2} m^3/h. The voltage of the arc, depending upon conditions of operation and design features of the plasmatron is about 10^2 V and the arc current, 10^2-10^4 A [2].

Control parameters of thermal and gas-dynamic characteristics of the jet of plasmatrons with permanent electrodes are the arc current, its length and flow rate of the plasma forming working substance. An increase in current and length of the arc leads to a temperature increase of the jet, its enthalpy and exit velocity; an increase in consumption of the working substance (gas) lowers the averaged mass parameters – temperature and enthalpy (Fig. 2).

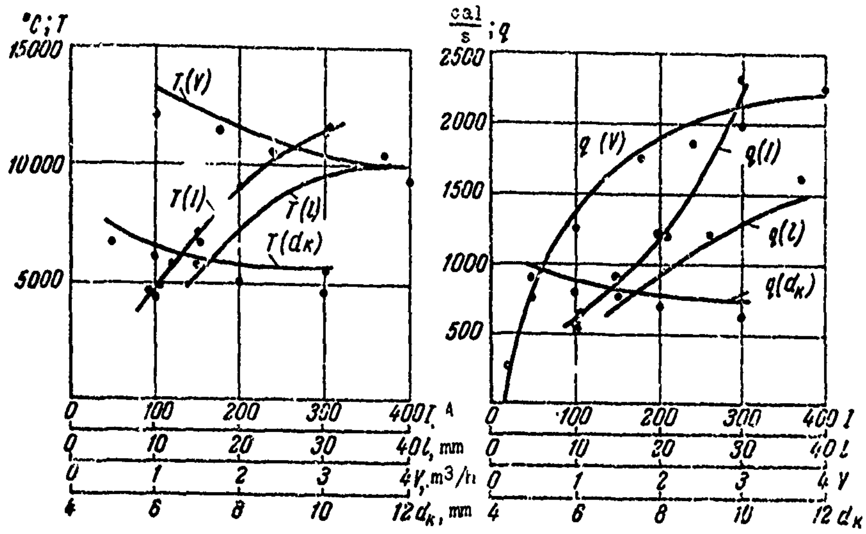

Fig. 2. Influence of basic parameters of operating conditions of an arc plasmatron (arc current, length of arc l, flow rate of gas V, diameter of nozzle of the channel d) on the averaged mass temperature T of plasma jet on the nozzle section and power of the plasma jet q.

The heat flow into substance interacting with the plasma jet is distributed over the spot of heating according to the law close to the probability curve of Gauss [3].

At present in the Soviet Union (the school of G. I. Petrov and others) and abroad (Fay, Ryddell, Kemp and others) there has been conducted extensive work on the creation of methods of calculation of processes of heat and mass transfer in the interaction of materials with high-temperature gas flow. For jets of dissociated gas ($T = 4000\text{-}6000^{\circ}$) important successes have been achieved. Expressions allowing calculation of heat flow with a sufficient degree of accuracy are obtained. For jets of ionized gas ($T = 8000\text{-}15{,}000^{\circ}$) the solution to the problem of heat and mass transfer requires calculation of the ambipolar diffusion, the effect of recharge, knowledge of transport sections of plasma components, Coulomb interaction of charged particles, calculation of plasma radiation, etc., which considerably complicates the problem.

Formation of the jet in the electrode region of the arc discharge. Energy processes on the discharge electrodes are formed in such a way that the removal of energy owing to the ablation of the electrode (first member of the right-hand side)

$$W = m\int_{T_e}^{T} C_p(T)\,dT - \lambda(T_e)\frac{dT_e}{dx} + \sigma T_e^4 \qquad (2)$$

was basic in the energy balance.

In plasmatrons operating on this principle, the plasma will be formed from evaporated substance of the electrodes (Fig. 3), which are continuously fed into the zone of the discharge [4].

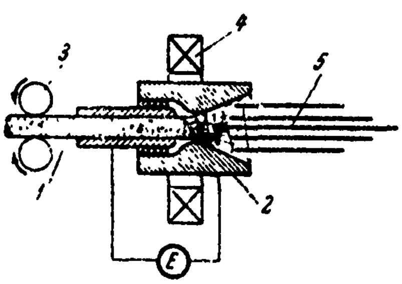

Fig. 3. Diagram of an arc plasmatron with a consumable axial electrode: 1 — electrode, 2 — nozzle, 3 — feed rollers, 4 — electromagnetic reel, 5 — plasma jet.

The temperature of plasma streams of a volatile material is 6000-10,000°, the enthalpy is 10-30 MJ/kg, and the speed of the plasma can reach hundreds of meters per second. The composition of the electrodes should have two requirements: first, products of its evaporation must correspond to the required composition of the plasma, and, secondly, the electrode should have the necessary electro- and thermophysical properties (relatively high conductivity and mechanical strength and relatively low thermal conduction). These requirements for electrodes somewhat narrow the possibility of the application of such plasmatrons, which, however, in a number of cases are more rational than plasmatrons operating on energy released in the plasma of discharge. For such plasmatrons the erosion of electrodes in principle is not a limiting factor, and they can operate in aggressive media (air, chlorine and others). The efficiency of the transfer of the worked substance into plasma, with a corresponding organization of energy conditions of the

discharge interval, can be higher than with plasma generation in the column of the arc.

High-frequency plasmatrons. Owing to the electromagnetic field plasma jets generate high frequency (1-30 MHz). Fed through a quartz tube with a diameter of 20-100 mm, which covers the inductor, is plasma-forming gas, most frequently with a twist. In the zone of the inductor under the action of high-frequency (hf) field currents heating the gas to a temperature of 8000-10,000° are induced (Fig. 4). Hf-plasma heads can work on any gases and their mixtures. Plasma jets, heating in the field of high frequency, differ by the greatest purity in chemical composition [5, 6].

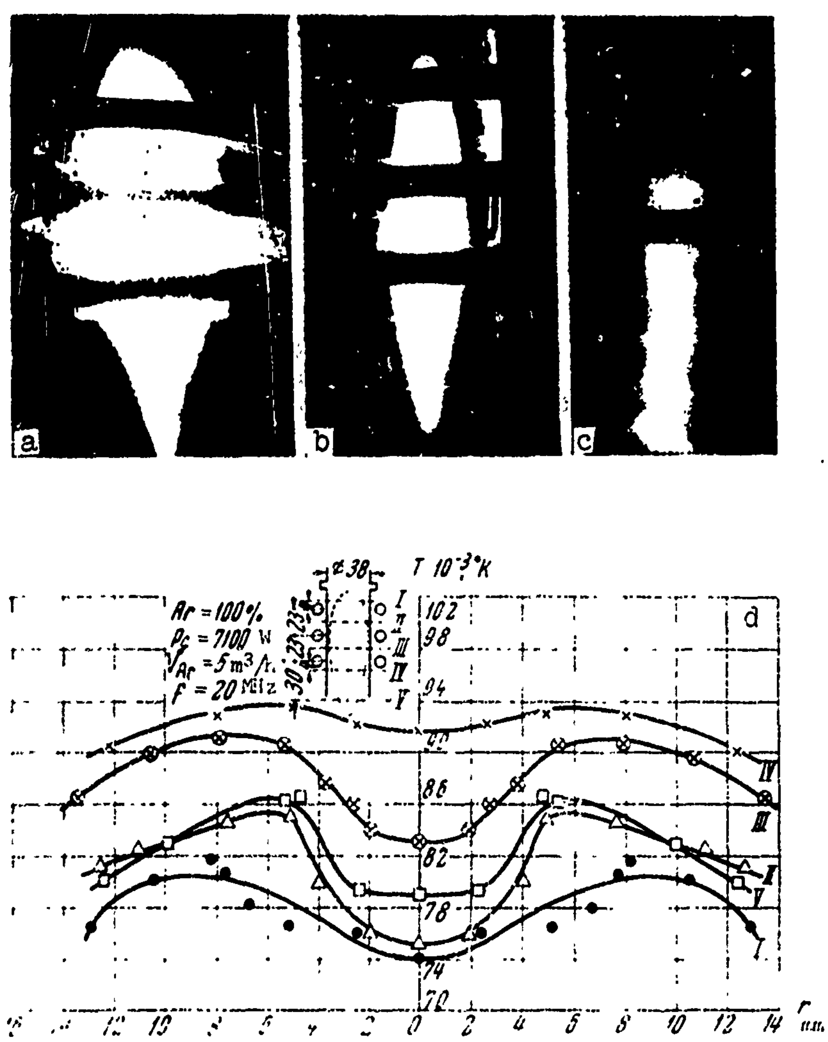

Fig. 4. High-frequency plasma jet: outer form of the plasma jet when operating on different gases: a) argon, b) osygen, c) nitrogen, d) radial distribution of temperature in different sections of argon plasma.

A hf-plasma jet can exist at a low exit velocity (several meters per second), which in a number of cases profitably distinguishes it from an arc plasma jet.

Dimensions of the plasma jet and character of the distribution of temperature in it are determined basically by the power of the discharge, diameter of the tube, kind and flow rate of the gas. When working with argon there was observed a collapse of temperature (800-1000°) along tha axis of the jet. The part of the power fed to the hf generator disperses on the anode of the transmitting tube, in the feedback circuit, housing of the high-frequency generator in the inductor, and also in the shielding housing of the apparatus. The total efficiency of the plasma generating apparatus reaches 60% at a supplied power of 100 kW.

The power introduced into the gas is changed little with the flow rate of the gas. Losses in energy of the jet for heating the walls of the quartz tube are sharply reduced with an increase in gas flow rate. With the introduction into argon of oxygen, nitrogen and hydrogen the diameter of the plasma jet noticeably decreases (Fig. 4a), and the walls of the quartz tube touch the less heated gas, in consequence of which losses in energy of the jet to heating of walls of the quartz tube are sharply reduced.

Means of development of plasmatrons. The diversity of technological fields of application of the jet present to plasmatron a number of special requirements.

Basic peculiarities of the organization of technological processes and their engineering shaping are the following:

1. In the engineering shaping of processes of the treatment of electrical conducting materials (cutting, melting, welding, etc.) two sources of energy are used: plasma jet and an electrically active arc spot. With this the efficiency of the process is naturally increased (Fig. 5) [7].

2. Requirements of processes of physicochemical treatment of powdery products (spheroidization of particles, obtaining of finely divided powder by the method of evaporation and restoration of oxides) led to the development of the various designs plasmatrons. Plasmatrons are built with magnetic twisting of the plasma jet [8]. In such plasmatrons there is promise in the creation of magnetic fields characterized by the induction of the order of several teslas (10-80 kgf) with the application of superconducting materials. Strong magnetic fields permit introducing energy into the plasma-forming gas (working substance) owing to Hall currents, which make it possible to lower the thermal load on the electrodes and impart an azimuthal rotation to the plasma.

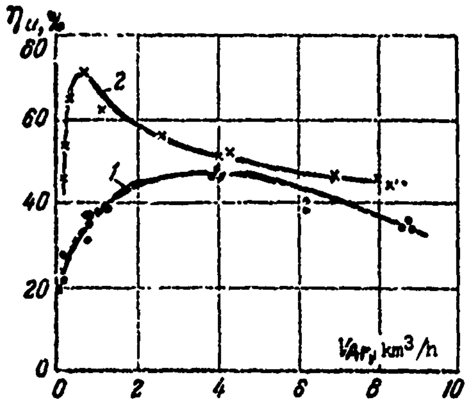

Fig. 5. Influence of the flow rate of gas on the effective efficiency of plasma heating at a different connection of the positive pole of the power supply: 1 — plasma jet, 2 — the same anode spot.

3. Plasmatrons with counter and pulsating jets are developed. The effectiveness of processes of heat exchange between the plasma jet and the treated powder in such apparatuses increases by approximately one order owing to the increase in relative velocity of the particle and plasma, time of stay of particles in the high-temperature region, and also turbulization of the flow.

4. At present plasmatrons of direct current are the most widespread. This is caused by a number of their advantages connected with the erosion of the electrodes, stability of burning of the arc and design shaping. However, powerful, at several MW, plasma generators of alternating current of industrial and increased frequency are promising. It is necessary to accelerate development of such plasmatrons.

2. Plasma Treatment of Materials

The most widespread use of jets of low-temperature plasma are found in such processes of technological treatment of materials cutting, surfacing, welding and impregnating with coverings.

These processes present to the plasma jet very diverse, sometimes contradicting to each other, technological requirements. For example, in surfacing it is expedient to disperse the heat flow of the plasma jet and reduce to a minimum its force action. In cutting it is necessary to concentrate the action of the jet on the smaller surface of the worked material and ensure the high exit velocity of the gas flow of the plasma jet.

Cutting and surface planing. In plasma cutting the metal is heated in the narrow zone up to a temperature exceeding the melting point and is carried from this zone by the gas flow of the plasma jet. The speed of cutting of steel sheets with a thickness of 5-10 mm approaches 1000 m/h, which is considerably higher than the speed of oxygen cutting.

For the cutting of metallic materials the most effective is the process of cutting by the plasma arc, when the cut article is the anode of the arc discharge (Fig. 1b). Electrically the separate plasma jet separated from the column of the arc which is burning between the tungsten electrode and nozzle of the plasma head, finds application mainly for the cutting of thin metallic sheets and nonmetallic materials. In welding it is desirable to concentrate the heat flow of the jet and simultaneously reduce the speed of its outflow. During 1956-66 a number of organizations developed and are now widely using the industrial application of plasma-arc cutting of metals. In maneuverability, nomenclature of objects of the treatment and in a number of cases in productivity and economy, this method exceeds machining and oxygen and arc cutting. In contrast to oxygen cutting, the plasma arc permits cutting practically all metals, including aluminum and copper and their alloys, high-alloy steel, refractory metals and nonmetallic materials which do not yield

to cutting by oxygen [9, 10]. The cutting of steel with thickness up to 40-60 mm is more productive by oxygen and flux cutting. As compared to the process of arc cutting, the productivity is increased by tens of times. The quality of plasma-arc cutting is comparable with the quality of cutting with oxygen cutting and exceeds that of flux and arc cutting. In practice there is checked the possibility of plasma-arc separating cutting of parts with a thickness of 0.5 to 300 mm and surface planing (Fig. 6). For cutting there must be plasma jets with the greatest concentration of energy (up to 10^6 W/cm^2 and a speed of 1000 m/s and higher). Such parameters of the jet are obtained owing to the great pressing of column of the arc discharge in the narrow channel of the nozzle of the plasma head (diameter of the nozzle in certain designs of plasma heads reaches 1 mm). To obtain narrow cuts (up to 100 μm) and holes of small diameter (50-100 μm) in the foil, at the Manfred von Ardenne Institute (German Democratic Republic) there are being developed plasma microheads having a diameter of the nozzle of 50 to 100 μm. Such dimensions and form of the nozzle and also the high pressure in the discharge chamber (50 at) ensure obtaining a plasma jet of an almost cylindrical form, flowing out of the nozzle at supersonic speed (3-4 M) [11].

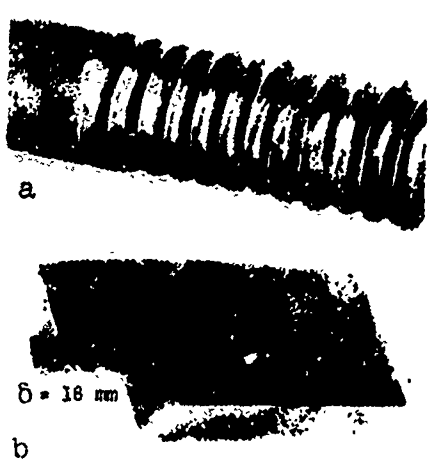

Fig. 6. Examples of the plasma of metal: a) planing (D. G. Bykhovskiy), b) cutting.

For realization of the process there has been developed cutting manual, universal and machine equipment with a power up to 200 kW, and many apparatuses have been manufactured.

Plasma-arc cutting is now widely being used by enterprises of shipbuilding, chemical, transport and heavy machine building, aviation and other branches of industry in the preparation of sheet parts, treatment of casting and forgings, pipe billets, continuous ingots and so forth.

Impregnating with covers and the manufacture of crust parts. Important applications of the plasma jet have been found for the creation of protective coverings on articles, operating at high temperatures and speeds of gas flow, in aggressive media, and also for the manufacture of complicated parts from refractory materials by the method of impregnating of a covering layer on the drawn pattern.

Owing to the high temperature the plasma jet permits applying layers of highly refractory materials with a melting point over 2500-3000° – tungsten, molybdenum, carbides of different metals, oxides, nitrides, borides and others.

Plasma coverings are characterized by low porosity, insignificant oxidation of the metal, great strength and higher cohesion with the base layer. An increase in temperature of the base layer improves the cohesion. The density of plasma coverings reaches 95-98%. Particles do not merge in a solid layer due to the high crystallization rate.

The process of plasma impregnating with coverings differs by high productivity, for example, the productivity of the atomization of carbide powder reaches 3-4 kg/h with an arc power of 40 kW. An even higher productivity (8-10 kg/h) is attained with atomization of tungsten wire. The method of impregnating with covering by means of atomization of wire was developed at the Institute of Metallurgy imeni A. A. Baykov during 1959-62 (Fig. 7). High productivity of the process is provided owing to the introduction into the plasma jet of a wire, which is the anode of the arc discharge. There has been developed a technology of impregnating with coverings of tungsten, molybdenum and niobium, properties of these coverings are studied,

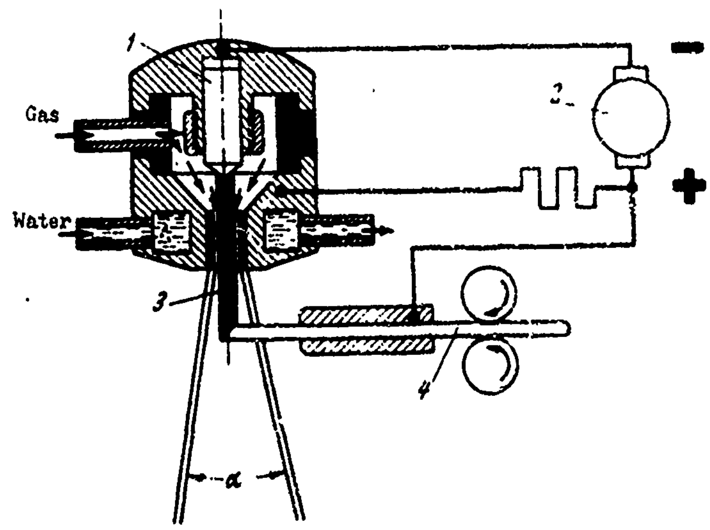

Fig. 7. Diagram of plasma impregnating with coverings by atomization of the current-carrying wire: 1 — tungsten electrode, 2 — power supply, 3 — arc column, 4 — atomized wire.

a method of the calculation of a plasma atomized head is developed, and vaporized coating conditions are being studied. Coverings of tungsten and molybdenum, impregnated on aluminum and rust-resistant and low-carbon steel, have adhesive strength with the base layer higher than the strength of the actual layer of the covering [12].

On the basis of these investigations, the industrial apparatus UMP-1-61 for the atomization of wire has been constructed.

Surfacing. The plasma jet permits fusing different refractory materials with a melting point higher than 2500-3000°, for example, carbides of tungsten and titanium, powders of alloys on the basis of tungsten, cobalt, chromium, nickel, iron and other elements, hard alloys of the stellite type, alloys with a high content of nickel, stainless steels, alloys with a copper base and a large number of other materials.

Basic advantages of plasma surfacing are as follows: the possibility of obtaining a thin fused-on layer, insignificant mixing of basic and fused metal, small deformations of weld metal due to the insignificant melting of the basic metal, lowering of

expenditures on subsequent machining and others.

The flexibility of arc plasma as a source of heat makes it possible to disperse and apportion quantities of heat introduced into the article and the fused metal.

The thickness of the layer can be controlled within limits of 0.25-5 mm, and the productivity of surfacing – from 0.5 to 5 kg/h. Materials of hard facing can be both powder, wire.

The mechanism of hard facing with a powder filler material consists in the following. A spot of an arc discharge rapidly heats and melts the surface of the article in the zone whose diameter is approximately equal to the diameter of the column of the arc. The powder fed into the head is heated and melted by energy of the plasma jet. Falling on the fused surface of the article, the particles of powder merge into drops, which in spreading form a dense layer of covering. The basic arc (electrode of the article) permits regulating the depth of the basic metal, and the auxiliary arc (electrode-nozzle) – the heating of the powder [13].

In the Laboratory of Welding of the Institute of Metallurgy imeni A. A. Baykov during 1961-62, the method of hard facing by a plasma jet with a current-conducting wire was developed (Fig. 8), which permits regulating the heating of the basic and filler metals so that the basic metal remains in a hard phase. By this method

Fig. 8. Macrograph of the cross section of a copper roller guided on a thin steel sheet by a plasma jet.

nonferrous metals are fused into steel and titanium in a number of enterprises of the country [14].

Welding. As compared to argon arc welding, welding by a plasma arc differs by higher speed and stability of the process. Owing to the cylindrical form of the column of the arc this process is less sensitive to oscillations of the length of the arc than the process of argon arc welding at which the change in length of the arc affects dimensions of the spot of heating and, consequently, the width of the seam [15].

Welding by a plasma arc is characterized a narrow and deep welding bath and deep melting of the basic metal, appearing due to the submersion of the arc spot into the metal (Fig. 9). By this method sheets of rust-resistant steel and titanium with a thickness of 12 mm are welded without working out of the edges [16].

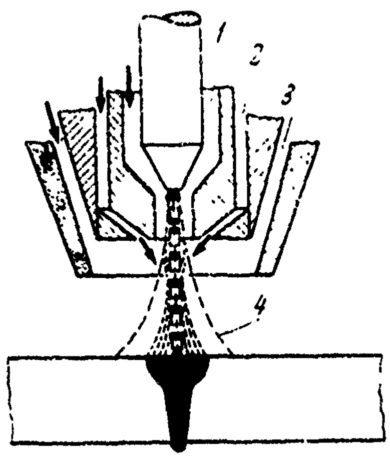

Fig. 9. Diagram of welding by a plasma arc: 1 — plasma-forming gas, 2 — focusing gas, 3 — protective gas, 4 — outline of the arc in the absence of focusing gas.

By the application of special plasma-forming nozzles the spot of heating with welding by the plasma arc can be given the needed form. To obtain a spot of stretched form in the nozzle there are made additional holes through which cold gas proceeds, which decreases the width of the spot of heating on this section. When welding by such a nozzle the zone of thermal influence narrows, and the speed of welding increases by 50-100%.

Advantages of the plasma arc in welding of longitudinal seams of pipes are especially important. Thus, for example, replacement of argon arc welding of rust-resistant pipes with a thickness of the wall of 2.3 and 7 mm by welding by plasma arc permitted increasing the speed welding by 50-200%.

3. Powder Metallurgy

Spheroidization of particles. The plasma jet permitted solving the problem of the obtaining of particles of different refractory materials (metals, alloys, oxides, carbides, nitrides and others), which are basis for powder metallurgy. Plasma technology is at present practically the only means of obtaining such particles.

Spheric particles are needed for the creation of cermet articles with assigned and uniform porosity operating under conditions of high temperatures, highly aggressive media and high speeds of gas and fluid flows. Spheric powders from refractory materials permit considerably increasing the working parameters for the articles.

Porous filters from refractory materials for the purification of fuel, oils, agressive liquids and gases help to increase the effectiveness of technological processes in chemical, metallurgic, food and other branches of industry.

At the Institute of Metallurgy imeni A. A. Baykov there are being developed methods of obtaining spheric powders of refractory materials by means of treatment in a plasma jet of wire and rods and also standard and granulated powders (Fig. 10). The material to be worked, which is introduced into plasma jet is heated, melted and, ing in a flow of hot gas, under the action of forces of surface tension acquires a spheric form. The hardening particles are collected in a special collector.

With treatment of the wire the most profitable with respect to productivity is a current with a current-carrying wire, when the arc burns between the tungsten electrode and atomized wire [17, 18].

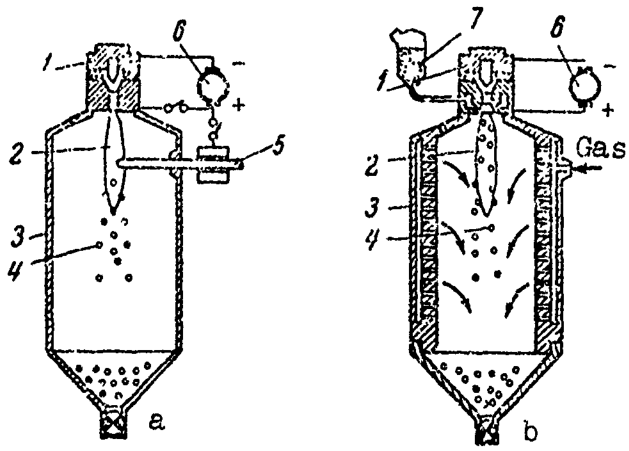

Fig. 10. Diagrams of spheroidization of powder: a) atomization rods in the arc plasma jet, b) fusion of initial powders in the arc plasma jet. 1 – plasma generator, 2 – jet of plasma, 3 – reactor, 4 – spheric particles, 5 – wire or rod, 6 – current source, 7 – initial powder.

Owing to the heating of the wire by the anode spot and current, there is attained 5-7 times higher productivity of atomization than with treatment of a neutral wire. The gas-dynamic pressure of the jet promotes a particular separation of drops of liquid metal forming on the end of the wire. Such a circuit provides high productivity of the process: 12-15 kg/h of spheric powder of tungsten at comparatively low power (18 kW) of the plasma head. By this method we obtain, for example, tungsten powders with the dimension of the particles from 100 to 400 μm (Fig. 11). Depending upon the conditions and material of the atomized wire, the fractional composition of the spheric powder can be considerably changed.

Wider possibilities are revealed in the processing in the jet of plasma of powder materials (Fig. 11b). In this case it is possible to obtain spheric particles of smaller fractions (from one micron to hundreds of microns) and not only from metals, but also from a large number of nonmetallic materials (oxides of aluminum and zirconium, titanium and chromium carbides and others). Spheric powders obtained by plasma processing, owing to the application of

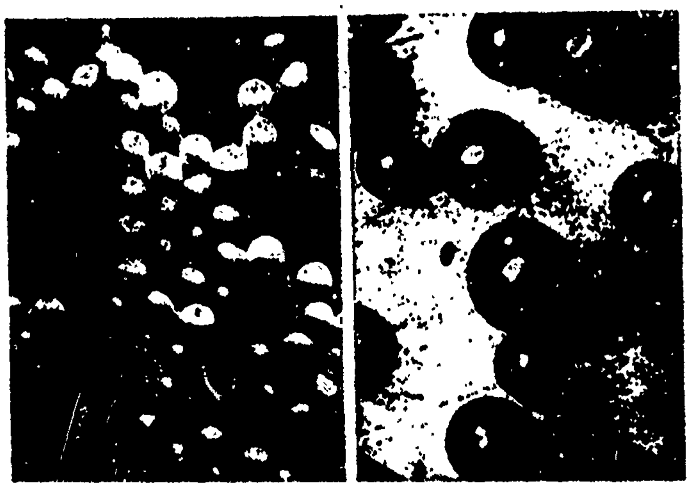

Fig. 11. Spheric powders: a) zirconium oxide with a dimension of 80-100 μm; b) tungsten with a dimension of 100-200 μm.

the inert sphere, preserve the cleanness of the initial material.

In the spheroidization of the preliminarily prepared granule together with provision of the form, a rather equal distribution of particles with respect to dimensions is obtained. The process of spheroidization of small standard powders occurs in a somewhat more complicated manner. In this case the unregulated union of particles of the initial material into conglomerates of diverse volume causes considerable distinction in the dimension of spheric particles (from fractions of a micron to several tens of microns), the separation of which in fractions is complicated.

On the basis of the investigations conducted the Institute of Metallurgy constructed an experimental apparatus for plasma spheroidization of refractory materials with a power of 100 kW.

In the obtaining of the plasma jet in the arc plasmatron a certain contamination of the worked material is possible by products of erosion of electrodes of the plasma generator. This deficiency is not present in plasma jets generated by the electromagnetic field of current of high frequency (hf) [19].

At IMET there have been developed hf apparatuses for plasma spheroidization of powders of refractory metals, oxides, carbides and other compounds. For the spheroidization of particles there is selected hf-discharge, the internal central zone of which is heated to a lower temperature than peripheral regions of the discharge. With this type of discharge it is easy to introduce the processed powder into the central zone of the plasma jet.

Treatment of the powder in pure plasma permits not only to rounding but also cleaning it of impurities; for example, with spheroidization of aluminum powder oxide a certain lowering of the content of oxides Na, Fe and Mg is observed.

Ultradispersed powders of metals and nonmetallic elements, nitrides, oxides and carbides obtained by the plasma method have recently attracted special attention of metallurgists, chemists, organic chemists. These powders have a specific surface of 10-100 m^2/g (diameter of particles, 1000-100 Å) possess high activity and are able to enter into direct reactions of synthesis with a number of organic and inorganic materials.

The pressing of different active ultradispersed powders can allow the obtaining of "pseudoalloys," which do not correspond to phase diagrams but represent a great practical interest.

Ultradispersed powders of pure elements can be used as catalysts and reagents in direct syntheses as surface-active substances and also for obtaining graft polymers. Powders of oxides, nitrides and hydroxynitrides can be used for coverings, the creation of new materials and so forth.

Powders of pure elements were obtained until recently by the evaporation of metals in induction and vacuum furnaces, chemical method, decomposition of compounds, and also in an intense electrical arc from consumable electrodes.

In the laboratory of plasma metallurgy of the Institute of Metallurgy jointly with the Institute of Chemistry, finely-dispersed powders of tungsten, molybdenum, titanium, nickel, aluminum and zirconium dioxide were obtained by means of evaporation in the plasma jet of initial standard powders with their subsequent condensation in flooded gas jets. Evaporation was conducted on an installation for the sphereidization of particles with the application of rigid conditions of treatment, which allow considerably to intensify heating of the treated material.

Electron-microscopic examinations showed that the dimension of particles obtained in such a way, are from hundreds to thousands of angstroms. The powders have spheric form, possess a very high specific surface and chemically are very active. The inert atmosphere permitted preserving the cleanness of the product, which differs little from the cleanness of the initial material.

Compounds of the type of nitrides and hydrides are obtained by selecting as the plasma gas the necessary reagent, for example, hydrogen or nitrogen. The development of this direction of technology depends in many respects on the organization of processes of "hardening" of the obtained compounds corresponding to the thermodynamic equilibrium, which corresponds to high temperatures created in the plasma jet.

4. Plasma Processes in Metallurgy

The possibility of obtaining by comparatively simple means of very high temperatures (10,000° and more) is especially important in the thermal decomposition of ores, in the melting and refining of high-temperature alloys and with synthesis of refractory compounds. At the same time the central most heated zone of the gas flow can be separated from walls of reactionary apparatuses by a layer relatively cold gas, in consequence of which requirements for the refractoriness of the material of walls are reduced, and the undesirable transition of components from the material of walls in products of reactions is practically excluded.

The temperature of the plasma jet, and this means thermodynamic conditions of the interaction, are easily regulated in wide limits.

The high concentration of energy in plasma heat sources opens up the possibility for a considerable increase in productivity of the process. The latter is promoted by high speeds of mass and heat transfer in the plasma jet. With this the "instantaneous" mass of the interacting substances can be small, which facilitates control of the process.

The possibility of a wide and independent control of the number and distribution of thermal sources, their intensity and geometric arrangement creates favorable conditions for accurate control by metallurgic processes.

Plasma sources by their nature permit easily carrying out an active physiochemical action on metallurgic processes by means of wide control of the composition and pressure of the gas phase and also by means of the application of slags whose composition is not limited to any conditions but is determined only by metallurgic requirements.

It is also possible to apply plasma sources of heat for the purpose of increasing the temperature of the process and creating a favorable atmosphere in the standard metallurgic units. Thus, for example, works are conducted on the intensification of gas burners in which the average temperature of the torch owing to its preheating by plasma of an electrical gas discharge is increased up to 2400°C.

In perspective it is possible to present the application of plasma heat sources for the intensification of electrometallurgic, open-hearth and blast-furnace processes.

Direct reduction of metals. Researches on the reduction of WO_3 and other compounds conducted at IMET showed the fundamental possibility of obtaining in a plasma jet pure powdery refractory metals from oxides and other compounds. For the reduction of

tungsten its trioxide heated in argon-hydrogen plasma. With this WO_3 is decomposed into tungsten and atomic oxygen. Depending upon the condensation point and the kinetics of heat removal, tungsten was obtained in the form of powders of different dispersiveness or in a compact state.

This means of the reduction of metals from their oxides, which allows considerably simplifying the technology of obtaining metals in different aggregate states, is very promising.

5. Plasma Remelt of Steels and Alloys

Some of the advantages of plasma heat sources in the application of pyrometallurgy can be shown in the example of plasma refining of alloys [20].

Plasma remelt (PP) is successfully carried out under the pressure of argon in a furnace of about 1 at. This eliminates the significant deficiency peculiar to vacuum-arc (VDP) vacuum processes and electronbeam (ELP) remelts — losses of alloy components as a result of evaporation.

A plasma furnace built at the Institute of Metallurgy has one, centrally located, plasma generator with a power of up to 100 kVA operating in conditions of an arc plasma jet between the cathode of the plasma generator and bath of liquid metal. Argon is used as the plasma-forming gas. A crystallizer 80 mm in diameter permits obtaining ingots weighing up to 15 kg (in the rating for steel). Consumable electrodes up to 30 mm in diameter move in a direction perpendicular to the plasma jet. Simultaneously up to three consumable electrodes are melted.

A peculiarity of the furnace is the combining of the thermal action of the central plasma jet of direct action (cathode to the crystallizer) with arc sources of heat formed by the inclusion of three-phase alternating current between the electrode. Such a combination of concentrated thermal sources expands the limits of

control of parameters of the process of remelting the metal and crystallization of the ingot and considerably increases the productivity of the process.

In this furnace the institute, jointly with the plant "Electrostal'," conducted works for determining the quality of metal of plasma smelting. Plasma remelt was applied to the heat-resistant alloy EI-617, steel ShKh-15 and an alloy of the permalloy type of a standard arc melt.

The experiments conducted permit making the following conclusions:

1. Plasma remelt provides ingots with good surface, not requiring roughing before forging or rolling. The chemical composition of ingots with respect to alloy elements (C, Al, Ti, Mn, Si, Mo, W and others) does not differ from the composition of the initial metal. The content of gases – O_2 and N_2 – in the metal after PP decreases by approximately 25-30%. It is necessary to note that the absence of changes in the composition of the metal with PP is an important advantage of this method in comparison with the DVI (which, for example, is not useful for refining of the metal alloyed by manganese and nitrogen).

It is possible to expect that the PP in this respect will appear more profitable in comparison with electron-beam melting, where the waste of volatile elements, for example molybdenum, reaches a considerable magnitude.

2 Plasma remelt considerably increases the quality of the metal. Thus, the remelt steel ShKh-15 permits lowering the point with respect to oxide inclusions from 2.2 to 0.7 and sulfide – from 3.4 to 2.0 (according to technical specifications TU 236-60). The hot plasticity of alloy EI-617 at 1000-1100° after remelting increased by 100% (a_k was changed from 8 to 16 kg-m/cm^2), the heat resistance – by 50% (the time up to destruction of samples at 850° and a load of 20 kg/mm^2 increased on the average from 80 to 120 hours) and placticity (lengthening and narrowing of samples with stretching) at 800° – on the average of 40-60%.

3. Plasma remelt as compared to VDP and electroslag remelt EShP possesses high stability of electrical conditions. The absence of short circuits and thrusts of current creates the possibility for eliminating in the cast structure of ingots such defects as layered crystallization, anisomerousness of the structure and others.

4. Plasma remelt as compared to VDP and EShP has considerably wider technological maneuverability. If with VDP the temperature and time of stay of the metal in a liquid state change insignificantly, then with PP these parameters can be controlled in a wide range, and, accordingly, it is possible to control the depth and form of the bath and the process of crystallization.

For the development and improvement of plasma processes of the treatment of materials the following is necessary:

a) on the basis of the study of the mechanism of elementary interactions, which determine parameters of plasma with energy of the particles of 0.5-5 eV, and the theory of heat and mass transfer in plasma, develop means of active control of processes of the interaction of plasma with the treated material;

b) investigate the physicochemical processes (phase conversions, kinetics of chemic ' reactions, processes of diffusion, accommodation, sorption, etc.) occurring on the surface of the treated material and in the boundary layer of the plasma.

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THE EFFECT OF MECHANOTHERMAL TREATMENT ON CYCLICAL STRENGTH OF WELDED SAMPLES OF TITANIUM ALLOY VT15

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An investigation is conducted of the cyclical strength of the base metal and welded samples of β-alloy of titanium of the VT15 brand, which are subjected to mechanothermal treatment. An analysis of the obtained data showed that the application of mechanothermal treatment of welded joints of alloy VT15 can considerably increase their longevity.

At present there are a number of works [1-6] in which there is investigated cyclical strength of pure titanium, α- and α + β-alloys of titanium. However, there are absolutely no data on the cyclical strength of titanium β-alloys, in particular, data on the fatigue of joints of these alloys.

In this work is conducted an investigation of the cyclical strength of the base metal and welded samples of titanium β-alloy of the VT15 brand (3.3% Al; 7.45% Mo; 10.5% Cr; 0.03% C; 0.35% N; 0.13% Fe; 0.07% Si; 0.006% H_2).

The possibility of the application of metastable titanium β-alloys in welded construction is limited in connection with the reduced plasticity of the welded joints, which is caused by the instability of the β-phase of the alloy with cooling in the process of the welding due to the development of the chemical and physical heterogeneity in the metal of the seam and zone of thermal effect.

For the purpose of studying the possibilities of the increase in efficiency of welded joints under conditions of alternating loads, one of the series of welded samples was subjected to mechano-thermal treatment (MTO) which consisted in rolling at room temperature of samples hardened after welding and subsequent aging. Mechanical properties and conditions of the treatment of the investigated series of samples are represented in Table 1. Samples of all series are subjected to hardening from a temperature of 1200°C (exposure of 15 min) in water and subsequent treatment according to conditions given in Table 1.

Table 1. Mechanical properties of samples from alloy VT15.

No. of series	Conditions of treatment		Mechanical properties			Remark
	Shrinkage ε, %	Conditions of aging	σ_b, kgf/mm^2	ψ %,	angle of bend α, deg.	
1	--	480°—18 h + 560°—15 min	$\frac{152-159}{157}$	$\frac{5-6}{5}$	$\frac{8-16}{12}$	Base metal
2	—	480°—18 h + 560°—15 min	$\frac{142-143}{142}$	0	$\frac{8-13}{10}$	Metal of welded seam
3	50	480°— 6 h + 560°—15 min	$\frac{147-166}{156}$	$\frac{2-5}{4}$	$\frac{10-10}{10}$	Base metal
4	50	480°— 6 h + 560 15 min	$\frac{133-151}{14}$	$\frac{0-3}{2}$	$\frac{10-27}{21}$	Metal of welded seam

Note. 1. Mechanical properties are determined on nonstandard samples 2 × 7 × 100 mm in dimension with bilateral grooves with a radius of 5 mm and width of the neck of 3 mm.

2. The numerator represents limits of the scattering of experimental data and the denominator — the mean value.

Selection of the temperature of hardening was caused, as the preceding investigations showed [7], by the fact that only after hardening from 1200° traces of intracrystal liquation in the metal of the welded seam completely vanish, and there occurs full dissolution of the α-phase, separated in the metal of the seam and weld-affected zone in the process of continuous cooling during welding. With this high chemical homogeneity of all sections of the welded joint is observed.

However, with hardening from 1200° the metal of the seam has very large polygonal grains, which in certain places are stretched along the direction of the primary columnar crystals. Inside the polygonal grains a coarse subgrained structure is developed (Fig. 1a).

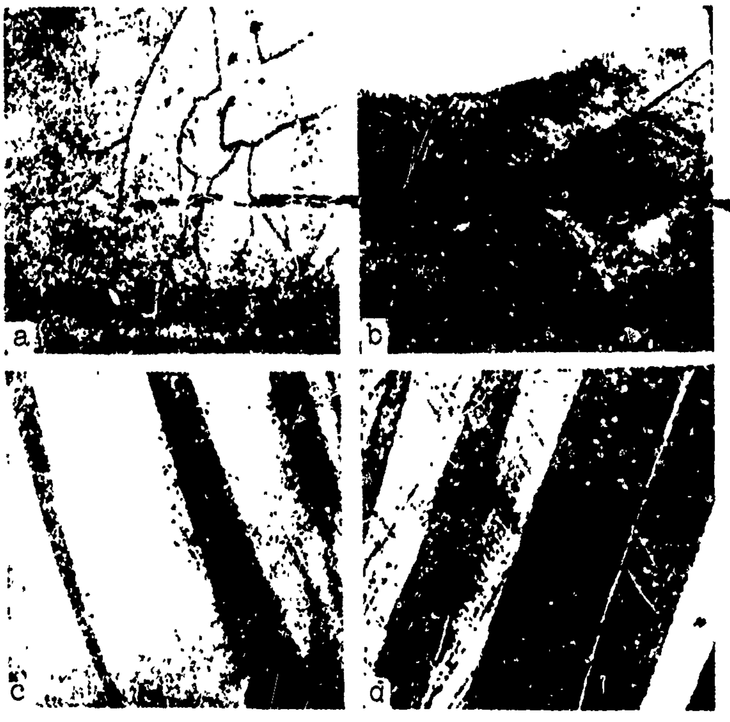

Fig. 1. Microstructure of alloy VT15:
a) metal of welded seam (series 4), ×100;
b, c) – base metal (series 3), ×200;
d) metal of welded seam (series 4), ×200.

The growth of the grain and coarsening of the structure lead to a lowering of plasticity of the base metal and welded joints. Therefore, high-temperature hardening can be recommended only before MTO.

The welding of samples of series 2 and 4 (Table 1) was conducted in one passage with the help of an automatic argon arc welding by a tungsten electrode according to standard procedure. Conditions of the welding of samples are given in Table 2.

Table 2. Conditions of welding of samples of alloy VT15.

No. of series	Thickness of sheet, mm	Diameter of tungsten electrode, mm	Welding current I, A	Voltage of arc U_g, V	Adjusting length of arc, mm	Speed of welding, m/h	Consumption of argon, l/min	
							For protection of arc (blowing out)	For protection of reverse side (blowing through)
2	1.0	1.6	40—50	10—12	1.0—1.5	20	8—10	2—3
4	2.0	2.0	90—100	10—12	1.0—1.5	20	12—14	3—4

After welding the samples, jointly with samples of the base metal were subjected to hardening from a temperature of 1200° in water after exposure at this temperature for 15 min. Samples of series 1 and 3 after hardening were subjected to aging according to these conditions: 480° – 18 h plus 560° – 15 min.

With MTO the samples (series 2 and 4), after hardening on β-phase, were subjected to deformation at room temperature. Deformation was carried out by rolling on a rolling mill during one passage of samples 2 × 25 × 100 mm in dimension, cut from the base metal or welded joints across the seam.

Since cold deformation accelerates the process of disintegration of the β-phase, samples after deformation were subjected to aging at shorter exposures (6 hours) than with the usual heat treatment (samples of series 1 and 3). In all cases the heating of samples for hardening and aging was produced in vacuum quartz ampules. Cooling from a temperature of hardening was produced by a division of ampules in water. The cinder forming was removed by hydrosand-blast cleaning and etching. Samples for fatigue test were prepared before aging.

As can be seen from Table 1, after hardening and aging the welded joint had lower indices of strength and plasticity (σ_b = = 142 kgf/mm^2, ψ = 0, α = 10°), than the base metal (σ_b = 157 kgf/mm^2, ψ = 5%, α = 12°).

As a rule, the MTO increases the strength of the metal as compared to the standard heat treatment [7], however, in metal of

given melt the MTO did not change the average strength indices of the base metal and welded joints (see Table 1). With this the plasticity of the base metal decreases (down to (ψ = 4%), and the plasticity of the metal of the welded seam somewhat increases (ψ = 2%). Therefore, this melt was selected for carrying out researches on series 1-4.

After hardening from 1200° for plastic deformation twinning becomes characteristic (Fig. 1c and d). Due to the metastability of the dispersed structure, obtained as a result of plastic deformation, scattering of results of mechanical tests is increased (σ_b = 147-166 kgf/mm^2 for the base metal and σ_b = 133-151 kgf/cm^2 for welded joints).

Fatigue tests of all series of samples were conducted on electromagnetic apparatuses [8] in which the excitation of oscillations of bracket secured samples with a concentrated ferromagnetic mass on the free end was carried out with the help electromagnets fed by alternating electrical current. The frequency of loading with alternating bend was 3000 cycle/min. The form and dimensions of the fatigue samples are shown in Fig. 2. The longitudinal axis of the welded seam is at the place of the maximum alternating stress (Fig. 2b).

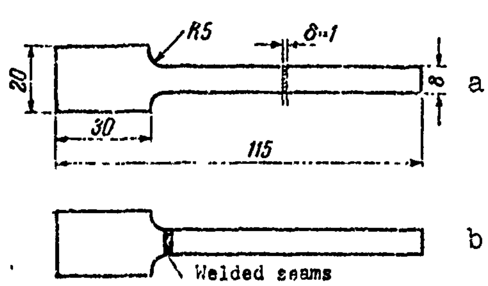

Fig. 2. Form and dimensions of samples for a fatigue test: a) sample of base metal; b) welded sample for fatigue test.

Results of fatigue tests are represented on Fig. 3. The fatigue curve of samples of the base metal (Fig. 3a) has a comparatively low fatigue limit – 24 kgf/mm^2 (at σ_b = 157 kgf/mm^2). However, it is necessary to consider that fatigue tests are conducted on samples with nonuniform distribution of stresses over the effective length (Fig. 2).

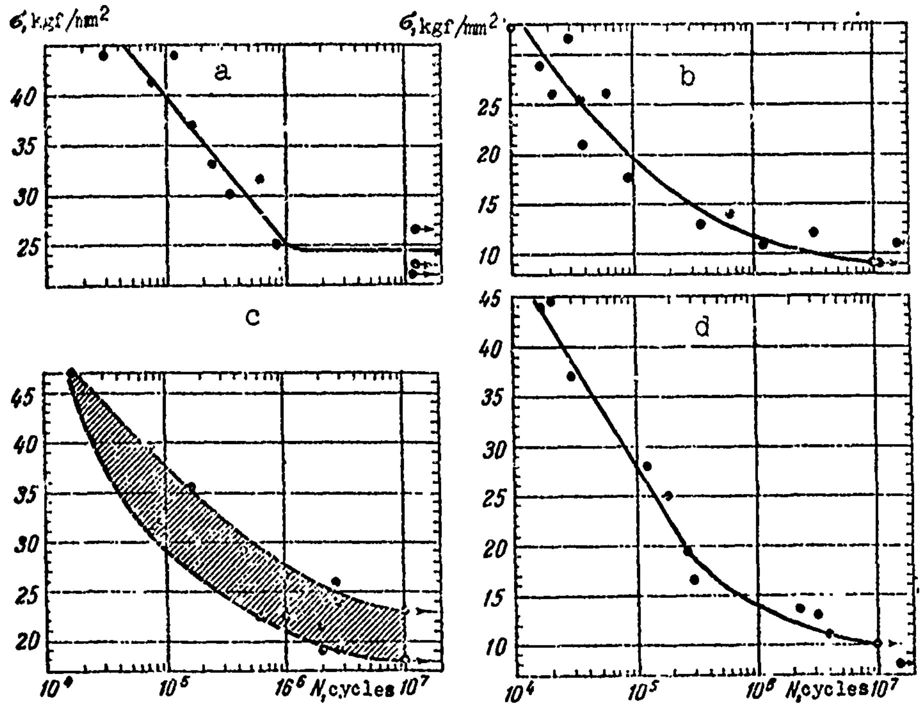

Fig. 3. Fatigue curves of samples of alloy VT15: a) base metal (series 1), b) welded samples (series 2), c) base metal (series 3), d) welded samples (series 4).

Welding sharply reduces the longevity and fatigue limit of samples (Fig. 3b) of the base metal (up to 11 kgf/mm²). This caused by creation in the welded seam of a structure with a large dimension of grain and well-developed coarse substructure. Furthermore, the lowering of cyclical strength of welded samples (series 2) is influenced by such factors as the presence of the transition zone from the base metal toward the seam and an additional surface concentrator of stresses from the line of transition of the welded seam toward the base metal.

The MTO of samples of base metal of this melt (series 3) did not lead to an increase in cyclical strength (Fig. 3c). As in the case of the determination of mechanical properties with static tension, great scattering of experimental data is observed. Therefore, the fatigue curve is drawn in the from of a scattering band. The fatigue limit of this series of samples along the lower envelope is considerably lower than the fatigue limit of

samples of base metal (18 and 24 kgf/mm^2, respectively) not passing the MTO. The longevity of samples of this series on all the studied levels of cyclical load is less or equal to the longevity of samples of the base metal not subjected to MTO.

Apparently, the carrying out of cold rolling with such a great degree of relative deformation (50%), not leading to an improvement in mechanical properties (see Table 1), only furthers the appearance of the damagability, in the alloy (for example, the appearance of submicroscopic cracks on borders of the block structure and mechanical twins). However, the MTO leads to a considerable increase in the longevity of welded samples (not changing the value of fatigue limit on the basis of 10^7 cycles of loading) on almost all levels of the cyclical loading (Fig. 4).

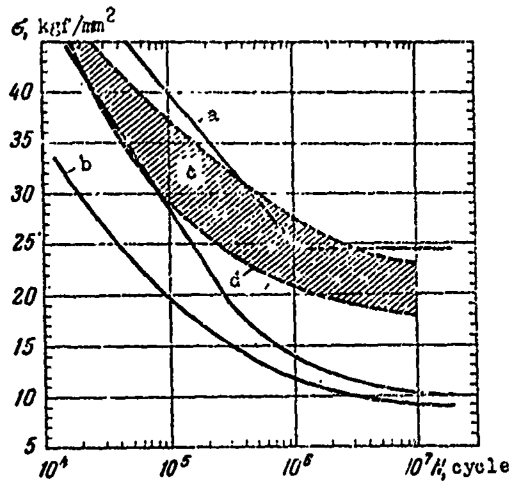

Fig. 4. Comparison of fatigue curves of samples from the VT15 series. (Designations are the same as those on Fig. 3).

In the region of low-cyclic fatigue ($N < 10^5$ cycles) the longevity of samples of base metal and welded samples of series (3 and 4) is almost identical (Fig. 4). Thus, the carrying out of MTO leads to a considerable increase in the longevity of welded joints of the alloy VT15.

An analysis of the destroyed samples showed that the destruction of samples of the first series almost always occurred on the most critical section. In the case welded joints (samples of series 2) destruction was observed both on the most critical section and

outside the dangerous zone nearer to the line of fusion. After MTO destruction of samples of the base metal and welded joints occurred on the most critical section.

It should be noted that only for initial samples of the base metal (series 1) is there observed a clearly expressed physical fatigue limit (fatigue curve has a sharp bend with emergence of the curve on the horizontal section). The absence of a clearly expressed physical fatigue limit for samples passing the MTO and welded samples (series 2, 3 and 4), apparently, indicates the presence in the structure of the alloy of damageability, which leads to the development of fatigue cracks. This damageability of the structure can be expressed in the form submicrocracks appearing with rolling in slip bands or on borders of mechanical twins, and also in the usual defects of welded seams.

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Conclusion. An analysis of data obtained in the work shows that the application of mechanothermal treatment for welded joints of titanium β-alloy of brand VT15 can considerably increase the longevity under conditions of cyclical load by alternating bend. The greatest increase in longevity (in 2-4 times) is observed in the region of low-cyclic fatigue ($N < 10^5$ cycles).

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THE MECHANISM OF THE FORMATION OF HOT CRACKS WITH WELDING OF NIOBIUM ALLOYS

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In a special technological test, used for an estimate of the resistivity of niobium alloys to the formation of hot cracks, measurements of deformations in the process of welding are conducted.

The measurements showed that cracks transverse to longitudinal stresses of shrinkage of a welded seam will be formed below the temperature of hardening of the welding bath. In these conditions destruction of the welded seams is close in scheme to destruction with high-temperature creep. A discussion is given of well-known models of intercrystallite destruction with creep in reference to conditions of cooling of the metal of the welded seam, and a hypothesis on the action of the vacancy mechanism of the formation of hot cracks is expressed. The resistivity of different alloys to intercrystallite destruction is determined by the relationship of speeds of slipping and migration of borders of the grains. An important role is played by the composition of alloys, the quantity of impurities of introduction and the character of their distribution in the cast structure.

The hypothesis is confirmed by results of metallographic analysis of structures and tests of alloys on a technological sample.

In welded joints of alloys with niobium as a base two forms of hot cracks are observed; longitudinal cracks in the beginning of the seam and small cracks along the seam in the direction of the growth of the crystallites during hardening. Such a location of the cracks is usually connected with the direction of the leading component of elastic-plastic deformation of metal of the seam in the temperature range of brittleness: across the axis of the seam from the edge of the sample and along the axis of the seam in the middle [1].

For an estimate of the resistivity of thin sheet niobium alloys to the formation of hot cracks during welding, a special technological test was developed [2]. A sample of the test is a plate 50 × 80 × 1 mm in dimensions with a cut parallel to the short side of the plate up to the middle of the sample. With melting of the sample the longitudinal axis of the seam passes through the vertex of the cut.

By special measurements conducted in the process of welding, it was shown that the deformation rate of metal in the vertex of the cut changes depending upon the location of the cut along the length of the sample, namely: with an increase in the section of the seam up to the cut the deformation rate increases [2]. This change is caused by an accumulation of shrinkage deformation in the section of the test sample up to the cut.

The first crack from the cut appears in the form of a local break along borders of grains in the seam. With an increase in speed of deformation small cracks develop into longitudinal cracks of great extent (Fig. 1a, b). The criterion of the estimate of resistivity of alloys to the formation of hot cracks is the length of the seam up to the cut at which the crack first appears.

It was of great interest to determine the temperature of the origin of the hot crack. For this purpose to the test sample in series with the cut there was welded a tungsten-rhenic thermocouple for recording the thermal cycle of welding on the tape of an

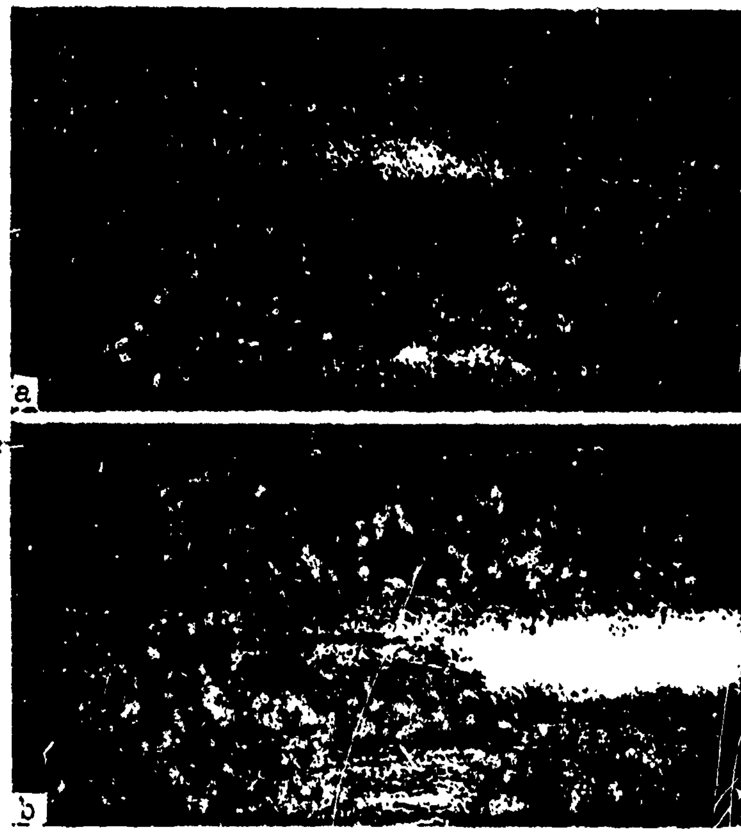

Fig. 1. Forms of cracks obtained in a technological test: a) transverse crack from the cut, b) crack along the axis of the seam.

oscillograph. Simultaneously on this tape with the help of a simple device displacement of the part of plate after the cut was recorded.

The device (Fig. 2) consists of a pointer, rigidly fastened to the plate, and an induction transducer, into the guide slot of which rests the pointer. Melting of the test sample was produced by a tungsten electrode in a medium of argon on the apparatus ADSV-2. Speed of welding was 25 m/h, and the welding current — 100-110 A. An oscillogram of curves of temperature and displacement is given on Fig. 3.

The recording very accurately in time reproduces the formation and opening of the crack and also the duration of the process of welding of the sample. The moment of the origin of the crack

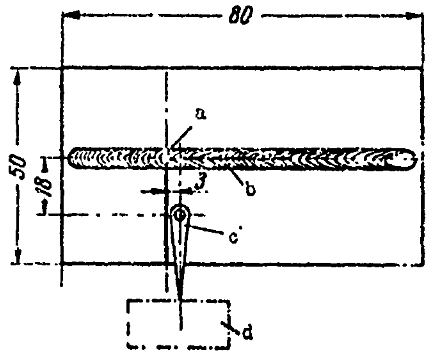

Fig. 2. Diagram of the device for the oscillographing of the thermal cycle of welding and displacement of the part of the sample after the cut: a) thermocouple, b) crack, c) pointer, d) induction transducer TL-2.

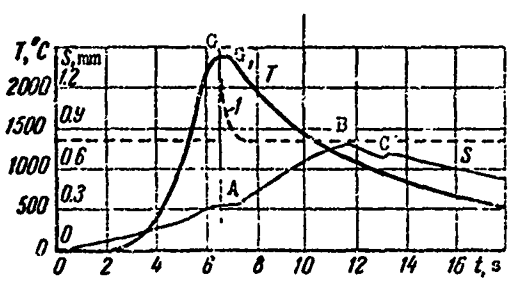

Fig. 3. Oscillogram of thermal cycle of welding $T = f(t)$ and displacement S of the part of sample after the cut. Speed of welding v = 20 m/h, 1 – moment of intersection by arc of the cut.

corresponds to a step on the curve of displacement (point A). The development of a longitudinal crack is recorded in the form of a segment of curve AB from the step up to the bend. Product vt_r (here t_r – time of development of the longitudinal crack determined by the oscillogram, v – speed of welding) accurately corresponds to the length of the crack on the sample. Point C is the end of seam, crater. On the curve of the thermal cycle the section GG_1 is the site of crystallization of the melting bath corresponding in time to the duration of the existence of the metal of the seam in a liquid or solid-liquid state.

A comparison of both curves of the oscillogram shows that the step on the curve of displacement (point A) appears on the branch of cooling of the temperature curve below the site of hardening GG_1. Consequently, the initial destruction of the seam from the cut occurs not on the liquid intercrystalline layers but in a solid state.

This observation is confirmed by results of the fractographic analysis of the surface of hot cracks (Fig. 4a, b). On fractographs longitudinal cracks fused dendrites, typical for the case of destru tion in a solid-liquid state, are very distinctive. On fractographs of transverse cracks and initial sections of cracks from cuts, large and small cavities of oval form with a spheric bottom covered with small pores are evident. Such a surface of cracks indicates that the destruction of metal occurs in a solid state.

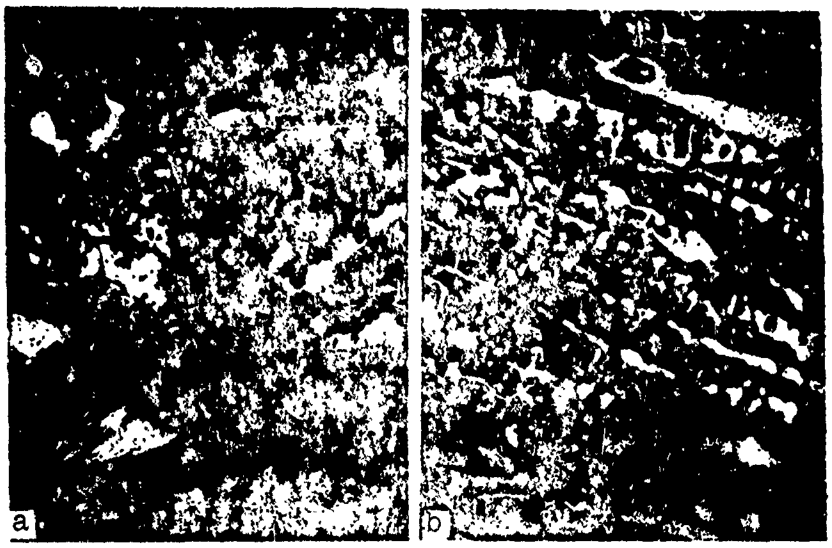

Fig. 4. Fractographs of the surface, ×300: a) surface of hot crack from the cut, b) surface of hot crack along the axis of the seam.

The mechanism of the formation of cracks of the first form (crystallization) is quite well studied and formulated in works [1, 3]. With the welding of niobium crystallization cracks are elim. ted by means of the fulfillment of certain simple operations: the use of technological plates for the striking of the arc o. displacement of the beginning at some distance from the edge of the joint if it is impossible to use technological plates.

The small transverse cracks appearing in the solid state cannot be eliminated by technological means. For a correct metallurgic approach to a solution of the problem, knowledge of the mechanism of formation of such cracks is necessary.

Destruction of welded seams below the temperature of hardening under conditions of growing stresses is very close in scheme to destruction with high-temperature creep. Below attempts are undertaken to estimate the known schemes of intercrystallite destruction with creep in reference to conditions of cooling of the metal of the welded seam.

According to the hypothesis of Zener [4], slipping along borders of grains where tangential stresses act leads to the concentration of tensile stresses on borders perpendicular to the axis of stresses, which creates cracks on the joint of the grains. However, observations show that hot cracks in seams, as a rule, do not start from peaks of the grains. Furthermore, the higher the temperature, the less the possibility of concentration of stresses in the joint of the grains. Finally, the predominant origin of cracks at the joint site assumes the absence of the migration of borders of grains [5].

At the same time in work [6] it is shown that in the process of cooling of ingots and welded seams of niobium, the borders of crystallization intensively migrate. Thus, the action of the Zener model under conditions of destruction of welded seams is improbable.

According to the hypothesis of Greenwood [7], intercrystallite destruction in the region of high temperatures occurs due to the separating of vacancies on borders perpendicular to the action of tensile stresses. The excess concentration of vacancies necessary for such separating appears with creep because of plastic deformation. It is established however, that this concentration is insufficient for the appearance of nucleate cavities of critical dimension [8]. Cavities will be formed only with intergrain slipping, revealing steps in the borders. Attaining the critical dimension with slipping, the cavities subsequently spread owing to the drain of vacancies.

Somewhat different conditions appear in welding. Due to the unbalanced process of crystallization, the metal of the welded

seam is extremely supersaturated with vacancies. One may assume that the concentration of vacancies in the seam at the temperature of fusion reaches 1.2×10^{-2} [9]. The equilibrium concertration of vacancies, determined by equation

$$C_0 = \exp\left(-\frac{Q_b}{kT}\right)$$

does not exceed at the temperature of fusion of niobium 1.74×10^{-4} (here $Q_b = 2.04$ eV [9] – activation energy of the formation of vacancies, T – absolute temperature, k – Boltzmann constant). Hence the degree of supersaturation by vacancies C/C_0 is 69.5, which is only twice less than the supersaturation necessary for the homogeneous origin of critical cavities.

In reality the supersaturation of welded seam by vacancies is even greater, since additional vacancies will be formed with the annihilation of dislocations in the migration rate of borders of grains. Another source of vacancies is tensile stresses of shrinkage, and the contribution of this mechanism should increase with the cooling of the welded seam.

On the other hand, the greater the ratio C/C_0, the less the energy of formation of the nucleate cavity and the more probable the formation [10].

Consequently, under welding conditions the possibility of homogeneous formation of cavities of critical dimension is not excluded, although by no means does this circumstance decrease the role of the intergrain slipping in the mechanism of destruction of the welded seams.

If cavities formed on borders of grains homogeneously or by means of slipping, are rapidly filled, and steps on the borders are smoothed, then intergrain destruction does not occur. In other words, the formation of cracks is determined by the speed of boundary diffusion. The expression of this dependence can serve as the bond between migrations of borders passing at high

speed and the absence of intercrystalline brittleness [5]. The border migrates into a new position deprived of distortions, and the nucleate cavity will not be formed.

The vacancy mechanism of the formation of hot cracks in welding finds direct confirmations with metallographic analysis of welded seams. On Fig. 5a a typical hot crack in the welded seam of alloy Nb-5%Mo is given. Here on borders transverse to the action of longitudinal shrinkage separate pores are noticeable. The grain porosity is noticeably strengthened after annealing of the plates with the welded seams (Fig. 5b).

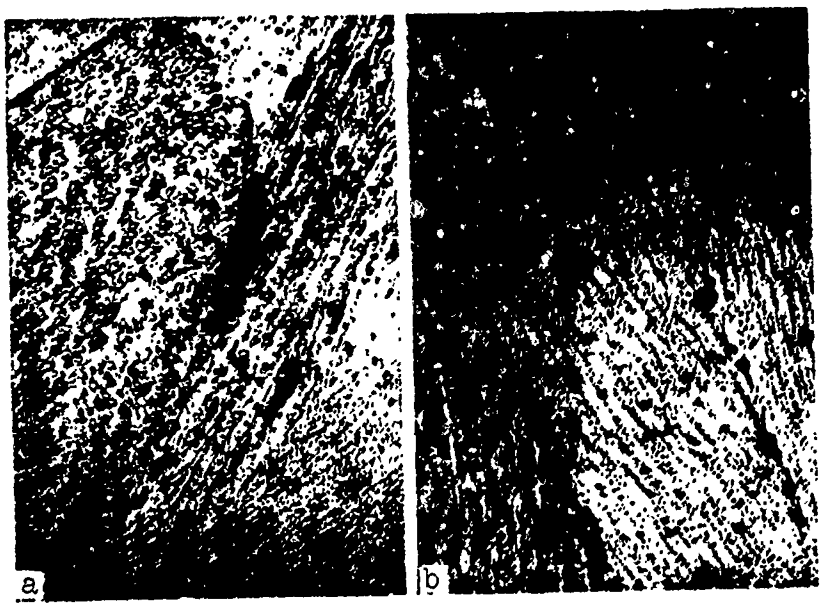

Fig. 5. Microstructure of a welded joint of alloy Nv-5 Mo, x150: a) hot crack and pores on transverse borders of the seam, b) pores on transverse borders after annealing at 1200°C, 1 hour.

Roentgenographic measurements, conducted according to the method of Berg and Barret, showed that transverse borders in the welded seams have the least angles of disorientation (5-10°). In accordance with the classification of Ost and Ratter [11] these borders are mean angular and relatively slightly mobile, which should promote the formation of nucleate cavities with slipping. Another result of the low mobility of borders is the predominate

segregation of vacancies and impurities on these borders, which facilities the opening of cracks owing to the decrease in the intergrain cohesion.

With argon arc welding of niobium of technical purity, hot cracks appear in the case when the content of oxygen and nitrogen in the base metal exceeds a total of 0.1% by weight. Elements of introduction, delaying the migration of the borders, promote both the formation of the nucleate cavities and opening of the cracks. With transition to electron-beam welding, the quantity of hot cracks in the metal of the seam decreases.

Here can the totality of three factors act: lowering of the quantity of impurity in the metal and, respectively on borders of crystallities; increase in speed of migration of the borders, i.e., decrease in the propability of the origin of cavities; increase in speed of cooling of the metal, i.e., decrease in the time of stay of the metal at temperatures of high diffusion of the mobility of vacancies and elements of introduction.

Very important is the question of the influence of alloy elements on the inclination of alloys to the formation of hot cracks in welding. Alloys of different compositions were investigated in a technological test. Experiments on the alloying of seams of niobium electron-beam remelting by foil of the following pure metals were also conducted: titanium, zirconium, molybdenum and tantalum.

Investigations showed that the alloying of niobium by elements forming the second phase (Zr, B, C) decreases the cracking of welded seams. There is a noticeable decrease in the inclination to the formation of hot cracks in solid solutions (Nb-W, Nb-V) of high concentration; however, the addition in niobium of molybdenum (5-10%) intensifies cracking of the seams.

Obviously, in alloying there are two counter processes: on the one hand, additions of alloy elements decrease the speed of the migration of borders and thereby increase the probability of

formation of the nucleate cavity; on the other hand, the alloying by elements, forming a high-temperature second phase or increasing the activation energy of diffusion in a solid solution, promotes the creation of uneven, fragmentary borders, about which slipping is hampered and nucleate cavities will not be formed.

High-temperature separatings on borders of grains can also act as fastening points and decrease the vacant length of the border, thereby lowering the concentration of stresses at places of the formation of nuclei [10].

The relationship of the mentioned processes is schematically represented on Fig. 6. The region of the formation of hot cracks is within limits of concentration of alloy elements O_1-O_2. In the alloy of composition O_1 the speed of migration of M borders is lower than the speed of the intergrain slipping B; in the alloy of composition O_2 the speed of slipping has a critical value B*, below which the formation of the nucleate cavity is impossible.

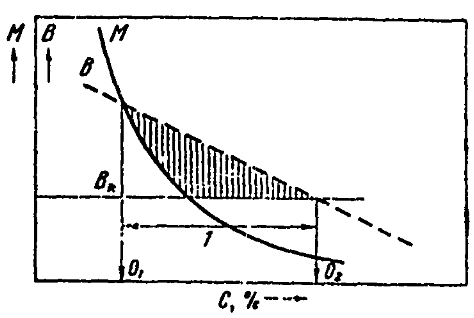

Fig. 6. Diagram of the mechanism of formation of not cracks: M — speed of migration of borders, B — speed of intergrain slipping, C — content of lay element, 1 — region of compositions of alloys with low resistivity to the formation of hot cracks.

The position of curves M, B_* and B on the diagram depends on the nature of the alloy element and the character of its interaction with the base and with impurities of introduction, and also on the quantity of excess vacancies in the alloy. Value B_*, furthermore, is determined, obviously by the rate of accretion of elastic-plastic deformation with cooling of the welded seam, namely, with an increase in the rate of deformation the critical speed of slipping decreases, which leads to the expansion of the region of concentrations O_1-O_2.

The diagram agrees well with results of metallographic investigation and tests of alloys of different compositions on a sample. Actually, in niobium of electron-beam remelting where the speed of migration is high, borders are rectilinear, and hot cracks with welding are absent. Cracks are absent in heterophase alloys. and in solid solutions of high concentration, where due to the low mobility of the border contours of dendrites of crystallization are repeated. Even the subsequent annealing of welded seams does not lead in this case to the formation of cavities on the borders.

Conclusions. 1. To estimate the resistivity of alloys of niobium to the formation of hot cracks in welding, a special technological test is developed. Measurements in the test showed that transverse cracks in a welded seam will be formed at a temperature lower than the temperature of hardening of the welding bath.

2. The hypothesis is advanced by which the cause of the origin of hot cracks is the separation of vacancies on borders of the grains. The appearance of nucleate cracks depends on the relationship of speeds of intergrain slipping and the migration of borders of grains, which in turn are functions of the composition of the alloy and quantity of impurities of the introduction.

3. The hypothesis obtained a number of confirmations with a test of niobic alloys of different compositions on a sample and with metallographic analysis of the structures.

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10 October 1966

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